Virtual residential gateways: Architecture and performance

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***Abstract*—With the increase of the transmission bit rate on optical fibers, it is now possible to transmit a radio base band signal over long distances. A very promising technology called Digital Radio Over Fiber (DRoF) uses this principle and allows centralization of resource management in the base station architecture. This architecture consists of three components: a Base Band Unit (BBU), a Remote Radio Head (RRH) and the interface between them such as CPRI (Common Public Radio Interface). In this paper, we propose to use the DRoF technology to virtualize current residential gateways making them less complex and allowing centralization of resource management. We show that the propagation delay can be a serious issue with Wi-Fi as we increase the distance between terminals and the access point.**

I. INTRODUCTION

In the last decade, high-bit-rate availability and competitive Internet Service Providers (ISP) offers have considerably increased the number of internet subscribers. To access the internet, those subscribers use generally a special device known as Residential Gateway (RGW) which is connected via an Digital Subscriber Line (DSL) connection to the ISP network (Fig. 1). In general, a RGW consists of an Ethernet card and a Wi-Fi access point to provide both wired and wireless access, and includes also an IP router with all common features such as Dynamic Host Configuration Protocol (DHCP) and Domain Name Service (DNS) that need to be configured. Even if default configurations are set by the operator, the customer is often lost when he needs to do some modifications.

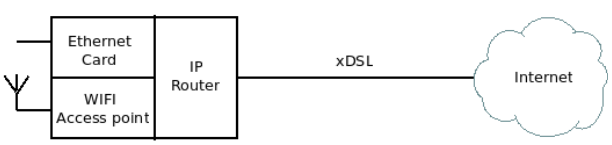

Fig. 1. Current residential gateway

To deploy devices as simple as possible in the customer premises, we propose to use the DRoF (Digital Radio Over Fiber) technology in order to virtualize RGWs. In the DRoF architecture [1], the access point is divided into two parts: a Remote Radio Head (RRH) that needs to be close to the antenna and a Baseband Unit (BBU) that can be several kilometers away from it. This is possible thanks to the high bit rate offered by optical fibers allowing the transmission of baseband signals over long distances. The general operation of the two components is as follow: in the downlink the BBU generates symbols from the digital baseband signal which consists of an in-phase (I) and a quadrature (Q) component. The signal is then sampled, quantized, modulated and transmitted over the fiber to the RRH, which is in charge of frequency shifting (the inverse process is done in the uplink). Of course, the use of a special interface between BBU and RRH, for example the Common Public Radio Interface (CPRI), is necessary.

A Wi-Fi access point can be splitted into a RRH and a BBU. The RRH stays in the customer premise (in the RGW) as it has to be close to the antenna, while the BBU can be shifted to the ISP network. To make the device even less complex, we propose to shift common RGW features (routing, DHCP, DNS,..) to the ISP. Thus, what remains in the customer premise is only a radio head and an Ethernet card, while all advanced features are centralized in the ISP network which allows a better resource allocation control, makes RGW easier to manage for the operator and reducing configurations to the customer.

As the RGW in no more a router all the local traffic is sent to the Wi-Fi-BBU, which was not possible before when access bit rates were limited to several Mbps. With new technologies such as Fiber To The Home (FTTH), customers can enjoy access bit rates up to several Gbps allowing virtualization of some RGW's advanced features.

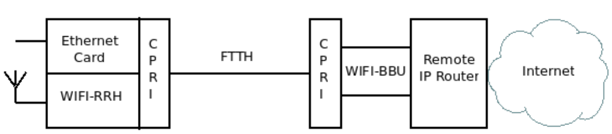

Fig. 2. Virtual residential gateway (vRGW)

The reminder of this paper is organized as follow. In section II we present briefly the CPRI interface. Section III describes how we intend to use the CPRI interface in the virtual residential gateway and section IV shows how Wi-Fi traffic can be transported over CPRI. Section V eventually concludes this paper.

II. CPRI OVERVIEW

CPRI [2] is an industry cooperation which defines the specifications for the interface between the RRH and the BBU. The specification defines only the protocols for layer

An extended abstract of this paper was accepted and published at EU-CNC'14.

1 (physical layer) and layer 2 (data link layer) making it restricted to the link interface.

The transmission in CPRI is organized in frames. A typical CPRI frame (Fig. 3) consists of 1 control word (CW) used for control and management, and of 15 data words transporting the IQ user data. A word can be coded in 1 byte, 2,...up to 16 bytes. Each word is always an integer number of bytes but transferred with 8B/10B coding. Consecutive control words produce a channel used for control, management and synchronization. As CPRI was initially proposed for UMTS, the frame rate is equal to the UMTS chip rate: $T_c = 1/3.84$ MHz ≈ 260ns.

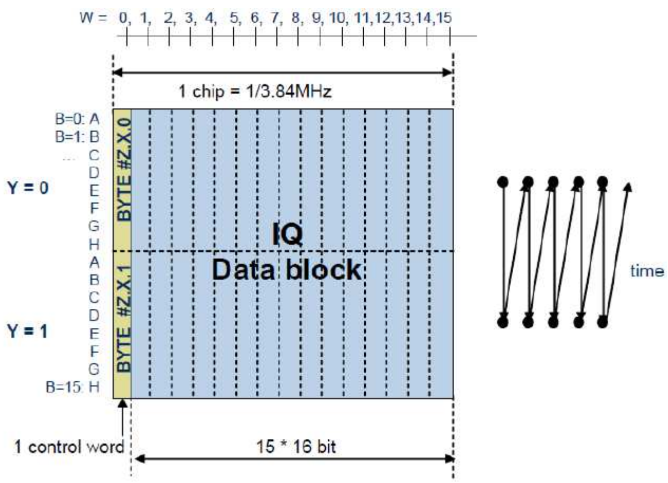

Fig. 3. One typical CPRI frame composed of two bytes words

The BBU generates modulation symbols with a sampling frequency f_s. These samples, which consist of M bits per component (I or Q), are then packaged into a so called AxC Container (Axc: antenna carrier). A typical AxC container is composed of a part or several IQ samples depending on the mapping method used. The AxC container size denoted by N_{AxC} is required to always be an even number (as many bits on the I and the Q channel). AxC container are then mapped in the IQ data block of the CPRI basic frame according to different possible methods.

IQ mapping method

For systems other than UMTS, the sampling frequency (f_s) is not always equal to the CPRI frame frequency ($f_c = 1/T_c$). The number of bits per frame is then equal to $2Mf_s/f_c$, note that this is not always an integer number. To be sure that all AxC containers have the same size, the specification defines the concept of AxC container block which spans over the minimum number of CPRI frames K such that it includes an integer number of samples S (Fig. 4). K and S are defined by:

$$K = \frac{\mathrm{LCM}(f_s, f_c)}{f_s} \tag{1}$$

$$S = \frac{\mathrm{LCM}(f_s, f_c)}{f_c} \tag{2}$$

where LCM stands for Least Common Multiple.

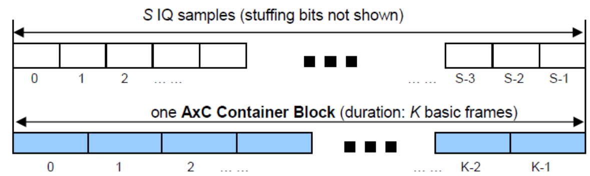

Fig. 4. Relation between S samples and one AxC container Block

1) Mapping method 1 (IQ sample based): This mapping method requires that an AxC container contains an even number of bits. N_{AxC} is then given by:

$$N_{AxC} = 2\lceil \frac{Mf_s}{f_c} \rceil. \tag{3}$$

Note that it is possible to have several IQ samples or a part of a sample within one AxC container. As the number obtained is rounded up, there is still some unused bits when the AxC container is mapped into the frame. This unused space is filled with stuffing bits that are placed in the beginning of the AxC container block. To know how many stuffing bits are necessary, we use:

$$N_{ST} = KN_{AxC} - 2MS. \tag{4}$$

2) Mapping method 2 (Backward compatible): In this mapping method, an AxC container contains one IQ sample only, its size is then equal to the sample size: $N_{AxC} = 2M$. However, it is possible to group several antenna carriers (AxC) with the same sampling frequency and the same sample width in a so called AxC Container Group. Let N_A be the number of AxC in one AxC container group. The AxC IQ samples are then multiplexed into a AxC container block consisting of N_C AxC container per basic frame, so $N_A S$ samples. In order to minimize the number of stuffing bits, the number of AxC container per CPRI frame is calculated with:

$$N_C = \lceil \frac{N_A S}{K} \rceil. \tag{5}$$

The number of stuffing bits per AxC container block is given by:

$$N_V = N_C K - N_A S. \tag{6}$$

III. CPRI INTERFACE IN VIRTUAL RESIDENTIAL GATEWAY

As we have seen in Fig. 2, a vRGW includes a Wi-Fi and an Ethernet interface. The traffic generated by both of them is transported through the CPRI interface over the fiber. Therefore, we suppose that the CPRI frame is divided into two parts: the first one is allowed to Wi-Fi traffic while the remaining space carries Ethernet frame (Fig. 5).

RGWs Ethernet interface is often a 1Gbps interface, but can be only a 100 Mbps interface in some cases. Hence, to be

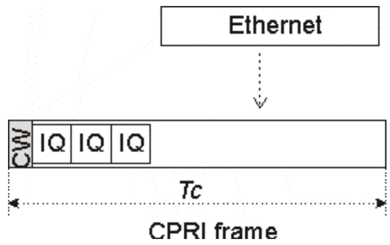

Fig. 5. Mapping Ethernet frame in the CPRI frame

able to transport the Ethernet traffic over CPRI, it is necessary that the remaining capacity is at least equal to the Ethernet interface bit rate.

IV. Wi-Fi over CPRI

As we presented before, CPRI acts as the interface between Wi-Fi-RRH in the vRGW and the BBU in the ISP side. In this section, we show how to transport Wi-Fi over CPRI using methods presented in II. Due to its popularity, all our study is about IEEE 802.11g but can be adapted to other standards.

First of all, let us notice that the 802.11g sampling frequency is 20 MHz [3] which is different from the CPRI frame frequency 3.84 MHz (II). Therefore, it is necessary to compute the AxC container block size K and the number of samples S it contains. As $f_s = 20$ MHz and $f_c = 3.84$ MHz, we have using (1) and (2) $K = 24$ and $S = 125$.

In order to determine which mapping method is most adapted for Wi-Fi, we calculate the number of RGWs that can be supported by the CPRI link. Indeed, FTTH is based on Passive Optical Networks (PONs). In a PON, several Optical Network Unit (ONUs) (located within the RGW) are connected to an Arrayed Waveguide Grating (AGW) (a passive device), this latter is then connected to a Optical Network Termination (ONT) through a single fiber link. Thus, it is necessary to optimize the link use so it can support as much RGWs as possible.

We also calculate the unused bit rate for each method. As seen in (III), this unused rate can be used to transport Ethernet traffic.

A. *mapping method 1*

We first compute the number of unused bits per CPRI frame, which is equal to the useful bits N (bits allowed to IQ data) per frame minus the number of unused bits:

$$N_b = N - N_{AxC} N_G. \tag{7}$$

Thus, the unused bit rate is equal to $3.84 N_b$ Mbps.

N_{AxC} is the AxC container size given by (3), and N_G is the number of AxC groups. We suppose that an AxC group contains samples from only one AxC, so N_G can be seen as the number of vRGWs. Using the fact that N_b have to be greater than or equal to 0, it is possible to compute the maximum number of vRGWs:

$$N_G \leq \frac{N}{N_{AxC}} \Leftrightarrow N_G = \lfloor \frac{N}{N_{AxC}} \rfloor. \tag{8}$$

B. *mapping method 2*

Using the same reasoning, we can compute the number of unused bits with:

$$N_b = N - N_{AxC} N_C \tag{9}$$

Since an AxC container consists of only one IQ sample, N_{AxC} is equal to the sample size $2M$. N_C is the number of AxC container per CPRI frame and according to (5), it is equal to $\lceil \frac{N_A S}{K} \rceil$. As it is possible in this method to have samples from several AxC container, N_A can be seen as the number of vRGWs.

Tables (6) and (7) show, for the two mapping methods, the maximum vRGWs that can be supported depending on the line bit rate, and taking into consideration the LAN interface rate. As seen in III, the unused bit rate can be used to transport Ethernet traffic. Hence, it is necessary that the remaining capacity is at least equal to the Ethernet interface bit rate.

The first column is the possible word sizes (modes) in the CPRI frame. The second one is the CPRI line bit rate we consider, "IQ bit rate" is the bit rate needed to transport Wi-Fi data and "available bit rate" is the unused bit rate calculated using (7) or (9). The last column is the bit rate allowed to each vRGW and has to be at least equal to the interface rate (Ethernet min rate). Note that when the unused bit rate is less than 1Gbps, we consider that the Ethernet card is a 100 Mbps interface.

CPRI Mode	CPRI Bit Rate (Mbps)	nb AP	IQ bit rate (Mbps)	Available bit rate (Mbps)	Eth min rate (Mbps)	Eth rate / AP (Mbps)
1	614,4	1	322,56	138,24	100	138,24
2	1228,8	2	645,12	276,48	100	138,24
4	2457,6	1	322,56	1520,64	1000	1520,64
5	3072	1	322,56	1981,44	1000	1981,44
8	4915,2	2	645,12	3041,28	1000	1520,64
10	6144	3	967,68	3640,32	1000	1213,44
16	9830,4	5	1612,8	5760	1000	1152

Fig. 6. Number of possible RGWs for different line bit rate (Mapping method 1)

CPRI Mode	CPRI bit Rate(Mbps)	nb AP	IQ bit rate (Mbps)	Available bit rate (Mbps)	Eth min rate (Mbps)	Eth rate / AP (Mbps)
1	614,4	1	368,64	92,16	100	92,16
2	1228,8	2	675,84	245,76	100	122,88
4	2457,6	1	368,64	1474,56	1000	1474,56
5	3072	1	368,64	1935,36	1000	1935,36
8	4915,2	2	675,84	3010,56	1000	1505,28
10	6144	3	983,04	3624,96	1000	1208,32
16	9830,4	5	1658,88	5713,92	1000	1142,784

Fig. 7. Number of possible RGWs for different line bit rate (Mapping method 2)

As we can see in Fig. 6, it is only possible to have a 100 Mbps interface for mode 1 and 2. However, if we look at Fig. 7 we can see that for mode 1, the available bit rate is less than the minimum bit rate required. Thus, it is not possible to have even a 100 Mbps interface for mode 1 when using mapping method 2. For the two methods, the maximum number of vRGWs is the same whatever the CPRI bit rate. We can see however that method 2 gives a better IQ bit rate than method 1 but in the other side method 1 provides a higher rate for Ethernet interface.

However, we can notice that it is necessary for both methods to have a line bit rate almost equal to 1Gbps to support at most 5 vRGWs.

C. Impact of the propagation delay

IEEE 802.11 MAC layer uses a random access to the medium based on the carrier sense (CSMA/CA) mechanism [3]. This means that a mobile terminal wishing to send data first needs to listen to the medium during a period called Distributed Interframe Space (DIFS), and can begin the transmission only if the carrier is free. However, if the propagation delay between two stations becomes too large they will not be able to sense the transmission of each other. More precisely, if station A is transmitting and the propagation delay to station B is larger than DIFS, B can believe that the medium is free and starts sending. Hence it, causes a collision. In other words, the collision probability is proportional to the propagation delay and so to the distance [4].

In our case, the fact that the BBU is moved to the end of the ISP increases considerably the propagation delay between the BBU and mobile terminals (Fig. 8). Indeed, the transmission speed depends mainly on the medium. In 802.11, the radio signal speed is approximately equal to 3.0×10^8m/s, while it is equal in the fiber to 2.0 x 10^8m/s (supposing that the delay added by intermediary devices such as AGWs is insignificant). The delay in the fiber is then reduced to $\frac{2}{3}$ of the radio propagation delay.

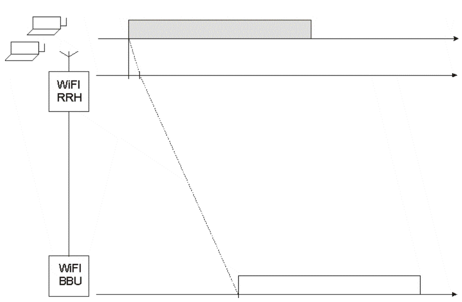

Fig. 8. Propagation delay in a virtual gateway Architecture

To evaluate the performances of Wi-Fi in a such architecture, we use the analytical approach developed by Bianchi [5]. Several assumptions have to be made in order to use the model.

We suppose first that there is a limited number of stations N and that the propagation delay between each pair of them is the same. The other key assumption is that each station operates in "saturation" conditions, which means that there are always a frame to be sent. This is a very strong assumption making the obtained performances undervalued. The different parameters we used for simulations are given in Table I where CW_{min} and CW_{max} are the minimum and maximum contention windows given by:

$$CW_{min} = W \tag{10}$$

$$CW_{max} = 2^m W \tag{11}$$

where W is equal to one time slot and m is the maximum back-off stage.

TABLE I. PARAMETERS FOR SIMULATIONS

Parameters	IEEE 802.11g
Transmission bit rate (Mbps)	54
MAC header (bytes)	34
ACK (bytes)	14
PHY Preamble + Header (bytes)	16+4
Slot time (s)	9
SIFS (s)	10
DIFS (s)	28
CW_{min}	16
CW_{max}	1024

To evaluate the performance, we look at the achieved throughput by a station in different situations. We vary the 3 main factors that can affect the throughput in a Wi-Fi network: the number of stations, the distance between them and the payload.

In the first case, we fixed the propagation delay to 9s (1.8 km through the fiber) and we varied the payload. We did this for different numbers of stations. In the other test, we fixed the payload to 1500 bytes and varied the propagation delay.

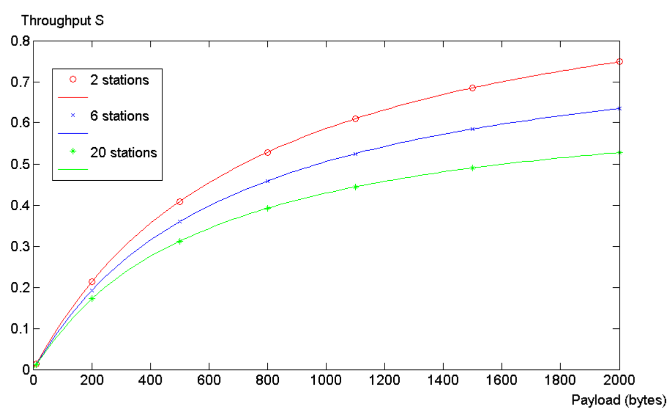

Fig. 9. Achieved normalised throughput vs. payload

Fig. 9 represents the results of the first test. It shows the achieved normalised throughput versus the payload when 2, 3 or 20 stations are sharing the medium. As it is expected, the throughput increases with the payload as more useful data are transported within one frame. However, the more the number of stations is the less the throughput is. This is due to the number of collisions which increases with the number of stations.

In Fig. 10, we can see the achieved normalised throughput as a function of the distance. Note that the propagation delay can be obtained given that the transmission speed over the fibre is equal to 2.0×10^8m/s. As we can see the throughput decreases as the distance grows which is due to the increase

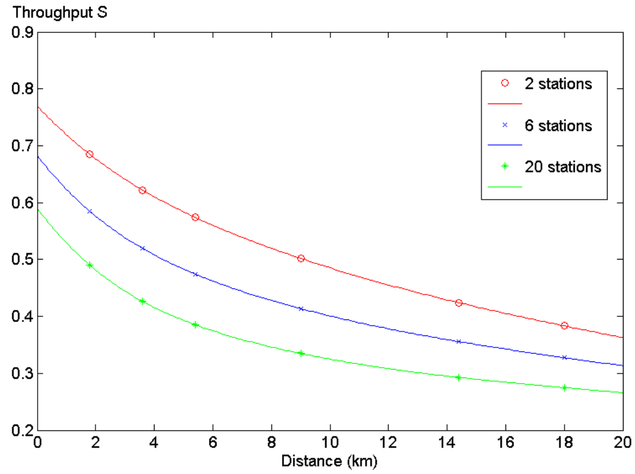

Fig. 10. Achieved normalised throughput vs. propagation delay (distance)

of the number of collisions. Like the first case, the throughput decreases also when the number of stations grows.

In a residential context, only a few stations are actives at the same time. If we look at the case of 2 active stations, we can see that the saturation throughput can be up to 70% of the transmission bit rate ($0.7 \times 54 = 37.9$ Mbps) when the distance between the BBU and the RRH is 2 kilometers. Even in case of high distances, we can see that the throughput never goes down than 40% of the transmission bit rate ($0.4 \times 54 = 21.6$ Mbps) which can be acceptable for users.

V. Conclusion

In this paper, we proposed to use the DRoF technology to virtualize the residential gateways making them less complex and allowing an easier management and control of resources allocation. We divided the residential gateways Wi-Fi access point into two parts : a Wi-Fi-RRH in charge of radio functions such as frequency shifting, and a Wi-Fi-BBU where all control and management features are put. The Wi-Fi-RRH stays in the gateway while the Wi-Fi-BBU is shifted in the ISP network and can be hundred of meters from the gateway. This is possible thanks to high bit rates offered by the fiber allowing the transmission of a baseband signal over long distances.

We first presented the CPRI interface and how to use it to transport Wi-Fi traffic. We used two methods described in the CPRI specification to map Wi-Fi traffic into CPRI frames. We then compared the two methods in term of number of residential gateways that can be supported by one CPRI link. We also showed that the remaining capacity can be used to transport Ethernet traffic. However, the fact that the BBU can be meters from the RRH increases considerably the propagation delay. Indeed, in Wi-Fi the collision probability increases with the propagation delay. To evaluate the performances of Wi-Fi in a such architecture, we the Bianchi model. We showed the relation between the achieved throughput and the number of stations, the distance and the payload which are the 3 main factors that can affect the throughput in a Wi-Fi network. We confirmed that the number of stations and the distance are directly related to the number of collisions.

This was a first study where we presented that the virtualization of residential gateways is possible using the DRoF technology. This can be very beneficial for management and control of the resources allocation as all this functions are centralized. However, a lot of issues have to be considered such as the influence of the distance in Wi-Fi networks and the very high bit rate that is necessary to support several gateways.

A lot of work remains in this domain. Future work can consist in specifying in detail how to virtualize the RGWs features, and to study in depth the resources management. It is also interesting to implement the solution and be able to give some real results in addition to simulations.

Acknowledgements

The research leading to these results has received funding from the European Communitys Seventh Framework Programme FP7/2013- 2015 under grant agreement no. 317762 COMBO project. We also thank Jinhuang Yu for the simulation results he provided.

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Virtual residential gateways: Architecture and performance (Extended Abstract)

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***Abstract*—With the increase of the transmission bit rate on optical fibers, it is now possible to transmit a radio base band signal over long distances. A very promising technology called Digital Radio Over Fiber (DRoF) uses this principle and allows centralization of resource management in the base station architecture. This architecture consists of three components: a Base Band Unit (BBU), a Remote Radio Head (RRH) and the interface between them such as CPRI (Common Public Radio Interface). In this paper, we propose to use the DRoF technology to virtualize current residential gateways (RGW) to make them less complex and to allow centralization of resource management.**

I. Introduction

Nowadays, customers use a special device called 'residential gateway' (RGW) to access the internet. An RGW consists of an Ethernet interface and a Wi-Fi access point (AP), it includes an access router with all common features such as Dynamic Host Configuration Protocol (DHCP) or Domain Name System (DNS). In addition of internet access, operators also use RGWs as Wi-Fi hotspots to provide their customers with Wi-Fi access whenever they are.

To deploy devices as simple as possible in the customer premises, we propose to use the DRoF (Digital Radio Over Fiber) technology in order to virtualize RGWs. Hence, the virtual RGW (vRGW) Wi-Fi access point can be divided into a Remote Radio Head (RRH) and a Baseband Unit (BBU). The RRH stays in the customer premise as it has to be close to the antenna, while the BBU can be shifted to the Internet Service Provider (ISP) network. In the downlink the BBU generates symbols from the digital baseband signal which consists of an in-phase (I) and a quadrature (Q) components. The signal is then sampled, quantized, modulated and transmitted over the fiber to the RRH which is in charge of frequency shifting (the inverse process is done in the uplink). To make the device even less complex, we propose to shift common RGW features (routing, DHCP, DNS,..) to the ISP.

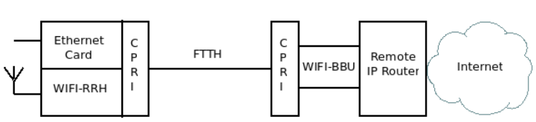

Fig. 1. Virtual residential gateway (vRGW)

This extended abstract was pulished at EUCNC'14

II. CPRI overview

Common Public Radio Interface (CPRI) [2] is an industry cooperation which defines the specifications (for layer 1 and 2) for the interface between the RRH and the BBU. There are several possible CPRI line bit rates, from 614,4 Mbits up to 9830,4 Mbits.

The transmission in CPRI is organized in frames. A typical CPRI frame consists of 1 control word (CW) used for control and management, and of 15 data words transporting the IQ user data. Consecutive control words produce a channel used for control, management and synchronization. CPRI was first proposed for UMTS transmissions, but it is possible to transport any base-band signal like Wi-Fi.

III. CPRI interface in virtual residential gateway

In vRGW, we propose to use CPRI to transport both the IQ signal (Wi-Fi) and and the Ethernet traffic over the fibre. Therefore, the CPRI frame is divided into two parts: the first one is allocated to Wi-Fi traffic while the remaining space carries Ethernet frame (Fig.2).

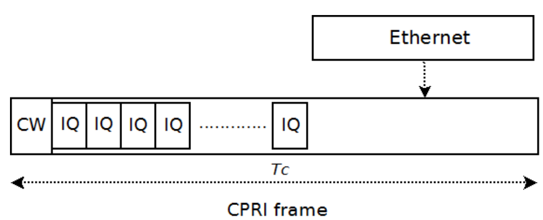

Fig. 2. Mapping Ethernet frame in the CPRI frame

RGWs Ethernet interface is often a 1 Gbps interface, but can be only a 100 Mbps interface in some cases. Hence, to be able to transport the Ethernet traffic over CPRI, it is necessary that the remaining capacity is at least equal to the Ethernet interface bit rate. Using the different mapping rules [2], we defined how to transport Wi-Fi and Ethernet in CPRI and computed how many AP can be supported for different line bit rate (in case of mapping method 1).

Tables (3) show, the maximum vRGWs that can be supported depending on the line bit rate, and taking into consideration the LAN interface rate. The first column is the possible word sizes (modes) in the CPRI frame. The second one is the CPRI line bit rate we consider, "IQ bit rate" is the bit rate needed to transport Wi-Fi data and "available bit rate" is the unused bit rate calculated. The last column is the bit rate allowed to each vRGW and has to be at least equal to the interface rate (Ethernet min rate). We notice the fact that when the unused bit rate is less than 1 Gbps, we consider that the Ethernet card is a 100 Mbps interface.

CPRI Mode	CPRI Bit Rate (Mbps)	nb AP	IQ bit rate (Mbps)	Available bit rate (Mbps)	Eth min rate (Mbps)	Eth rate / AP (Mbps)
1	614,4	1	322,56	138,24	100	138,24
2	1228,8	2	645,12	276,48	100	138,24
4	2457,6	1	322,56	1520,64	1000	1520,64
5	3072	1	322,56	1981,44	1000	1981,44
8	4915,2	2	645,12	3041,28	1000	1520,64
10	6144	3	967,68	3640,32	1000	1213,44
16	9830,4	5	1612,8	5760	1000	1152

Fig. 3. Number of possible RGWs for different line bit rate (Mapping method 1)

As we can see, it is only possible to have a 100 Mbps interface for mode 1 and 2. For other modes, it is possible to have a better interface bit rate but the number of AP supported can be decreased (e.g mode 3 and 4). The important thing we can notice, is that even with the best CPRI line bit rate (9830,4 Mbits) it is only possible to have 5 RGWs.

A. Impact of the propagation delay

The fact that the BBU is moved to the end of the ISP increases considerably the propagation delay between the BBU and mobile terminals (Fig. 4). In Wi-Fi, the collision probability is proportional to the propagation delay and so to the distance [4]. In 802.11, the radio signal speed is approximately equal to 3.0×10^8 m/s, while it is equal in the fibre to 2.0 x 10^8 m/s (supposing that the delay added by intermediary devices such as AGWs is insignificant). The delay in the fibre is then reduced to $\frac{2}{3}$ of the radio propagation delay.

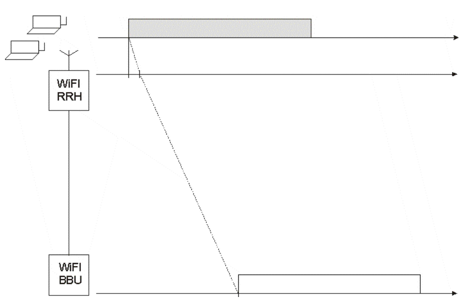

Fig. 4. Propagation delay in a virtual gateway Architecture

We use the Bianchi model [5] to get the throughput for different configuration. We suppose that there is a limited number of stations N and that the propagation delay between each pair of them is the same. Each station operates in "saturation" conditions, which means that there is always a frame to be sent. This is a very strong assumption making the obtained performances undervalued. The different parameters we used for simulations are given in Table I below [4] where CW_{min} and CW_{max} are the minimum and maximum contention windows.

Fig. 5 shows the achieved normalised throughput as a function of the distance. The propagation delay is computed for a transmission speed over the fibre equal to 2.0×10^8 m/s.

TABLE I. PARAMETERS FOR SIMULATIONS

Parameters	IEEE 802.11g
Transmission bit rate (Mbps)	54
MAC header (bytes)	34
ACK (bytes)	14
PHY Preamble + Header (bytes)	16+4
Slot time (s)	9
SIFS (s)	10
DIFS (s)	28
CW_{min}	16
CW_{max}	1024

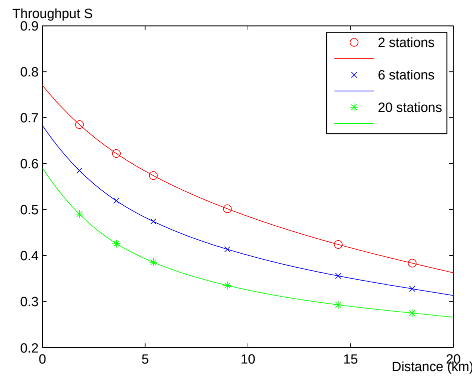

Fig. 5. Achieved normalised throughput vs. propagation delay (distance)

As we can see the throughput decreases as the distance grows which is due to the increase of the number of collisions.

In a residential context, only a few stations are actives at the same time. If we look at the case of 2 active stations, we can see that the saturation throughput can be up to 70% of the transmission bit rate ($54 \times 0.7 = 37,9$ Mbps) when the that separates the BBU and the RRH is 2 kilometers. Even in case of high distances, we can see that the throughput never goes down than 40% of the transmission bit rate ($54 \times 0.4 = 21.6$ Mbps) which can be acceptable for users.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Communitys Seventh Framework Programme FP7/2013- 2015 under grant agreement no. 317762 COMBO project. We also thank Jinhuang Yu for the simulations results he provided.

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